Exploring the QCD phase diagram with collective flow at STAR

Shusu Shi

for the STAR Collaboration

Central China Normal University

Supported in part by U.S. DEPARTMENT OF ENERGY

Outline

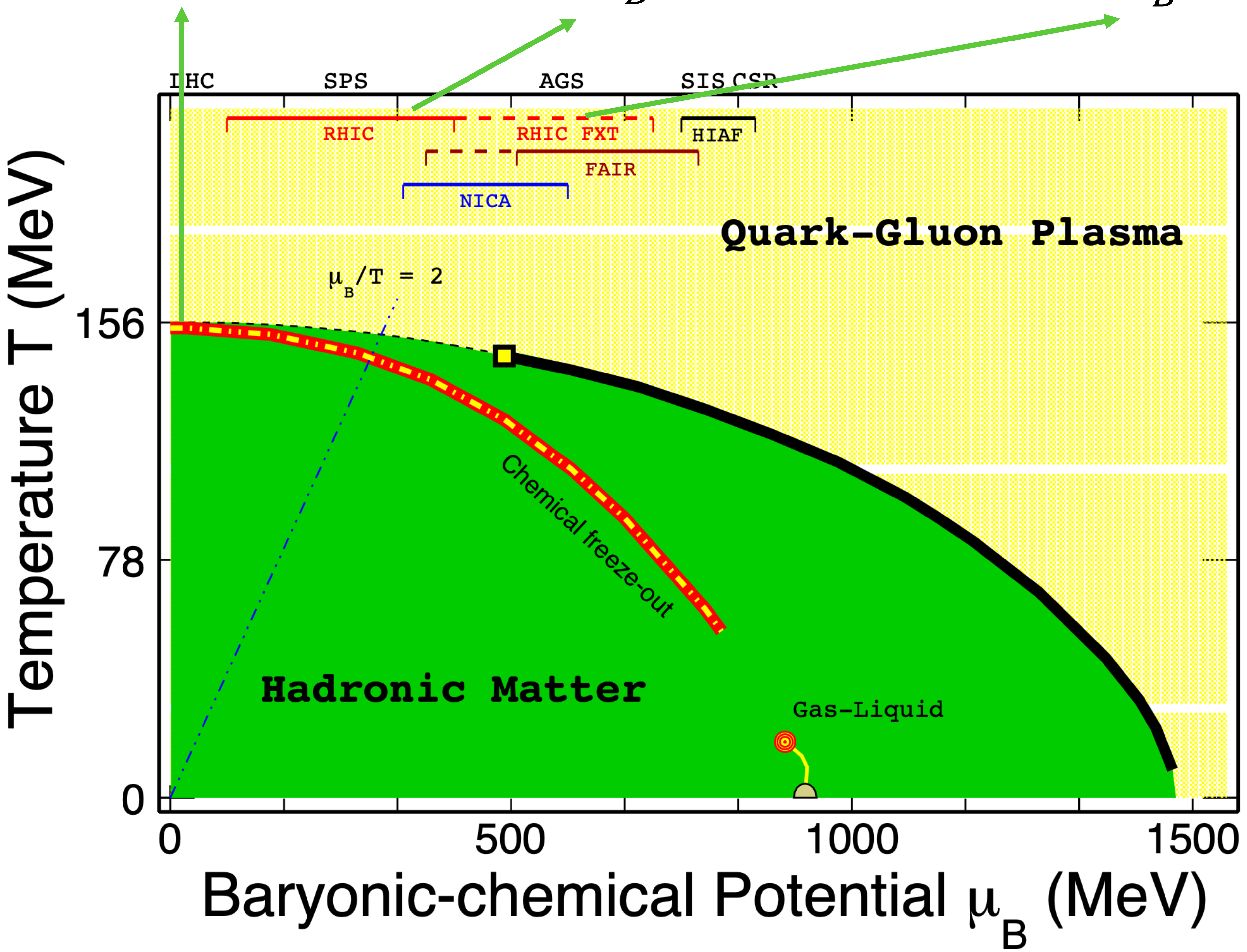
- **Motivation**
- **Experimental Setup**
- **Results and Discussion**
  - Directed flow (v_1)
  - Elliptic flow (v_2)
- **Summary**

Motivation

LHC, RHIC 200 GeV
Tc

RHIC COL: 7.7-62.4 GeV
u_B: 420-73 MeV

RHIC FXT: 3.0-7.7 GeV
u_B: 750-420 MeV



A. Bzdak et al., Phys. Rept. 853, 1 (2020); X. Luo et al., Particles 3, 278 (2020)

- **RHIC 200 GeV and LHC**

  Study the properties of Quark-Gluon Plasma

- **Beam energy scan program**

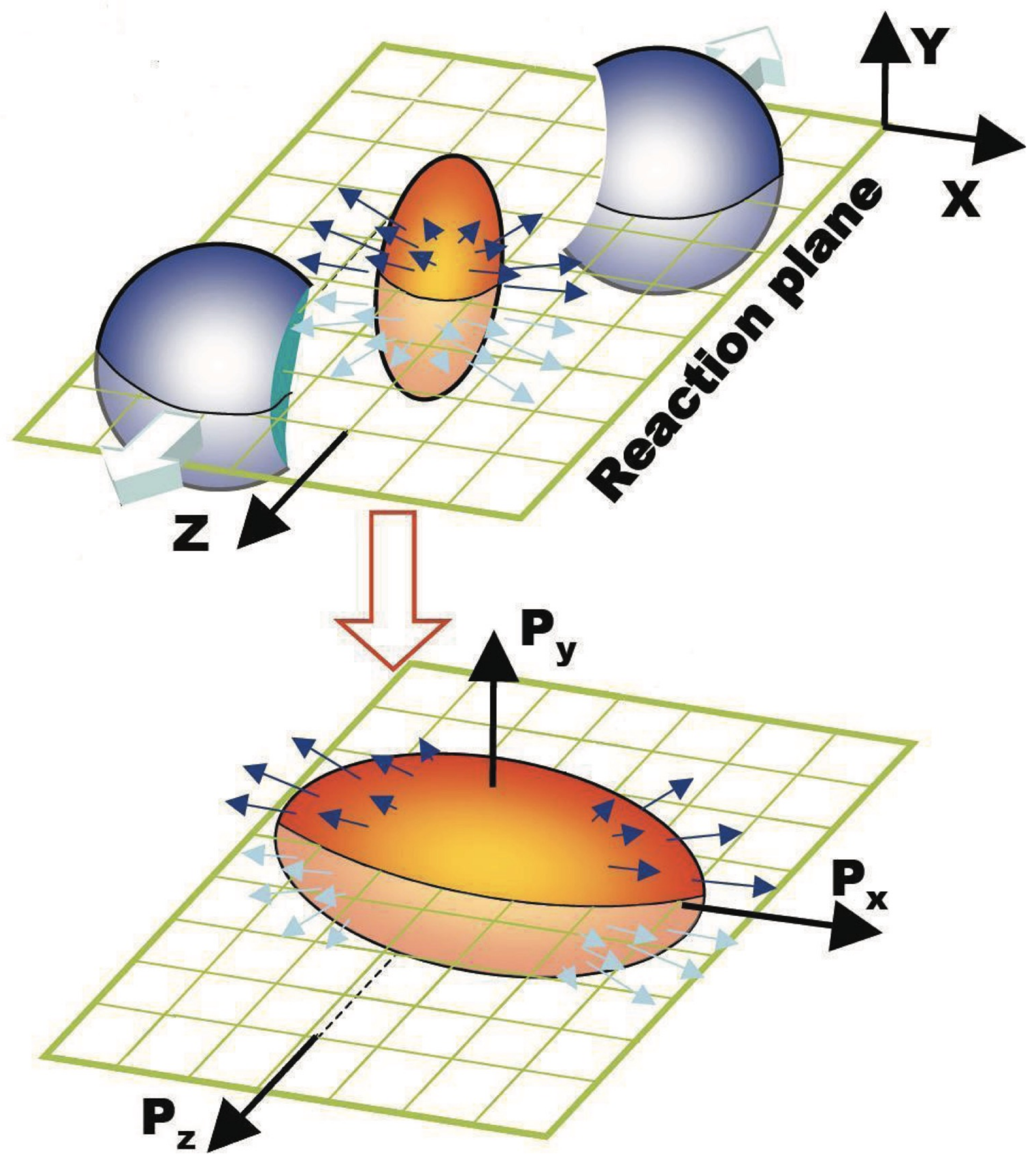
  Locate the first-order phase boundary

  Search for Critical Point

Anisotropic flow

Anisotropies in particle momentum distributions relative to the reaction plane

Initial spatial anisotropy → Pressure gradient → Momentum space anisotropy



$$E\frac{d^3N}{dp^3} = \frac{1}{2\pi}\frac{d^2N}{p_T dp_T dy}\left(1 + \sum_1^{\infty} 2v_n \cos[n(\phi - \psi_r)]\right)$$

$$v_1 = \cos(\phi - \psi_r) = \langle\frac{p_x}{p_T}\rangle$$ directed flow

$$v_2 = \cos[2(\phi - \psi_r)] = \langle\frac{p_x^2 - p_y^2}{p_x^2 + p_y^2}\rangle$$ elliptic flow

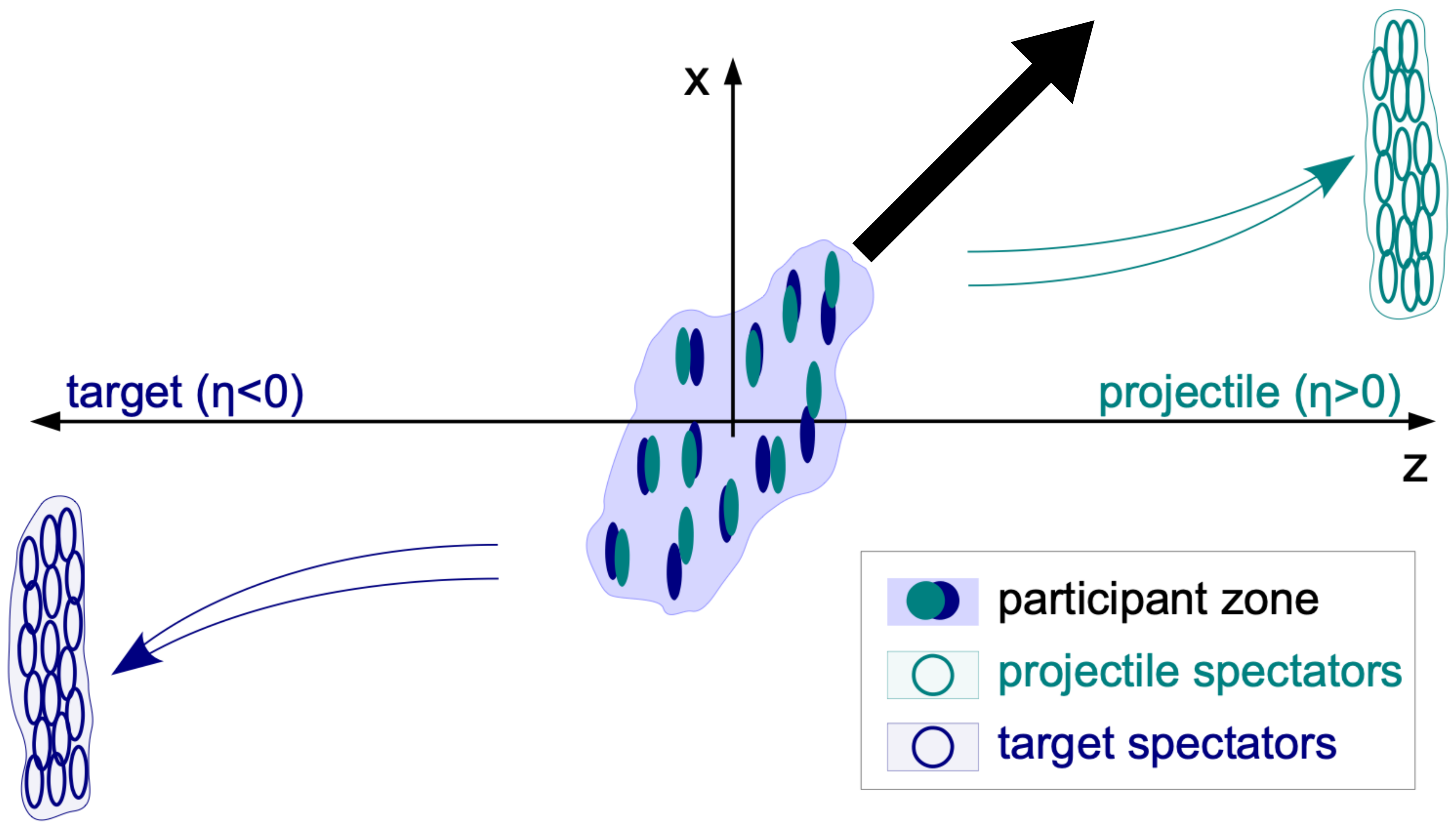
- **Equation of State**
- **Degree of Freedom**

A. M. Poskanzer and S. A. Voloshin, Phys. Rev. C 58, 1671 (1998)

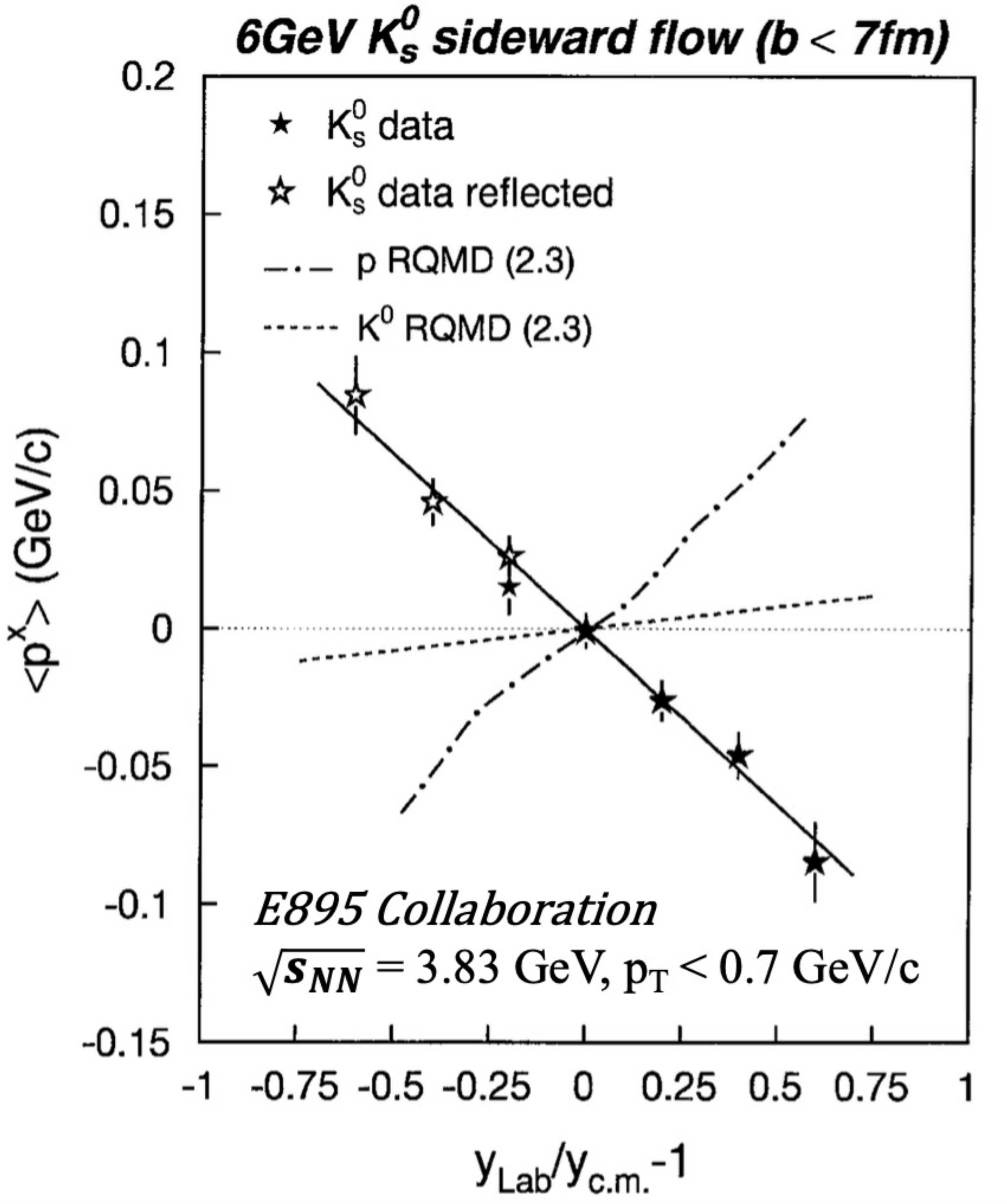
P. Danielewicz, R. Lacey, Science 298 (2002)
STAR, Phys. Rev. Lett. 118, 212301 (2017)

Motivation: Anti-flow of v_1

Figure: Phys. Rev. Lett. 111, 232302 (2013)



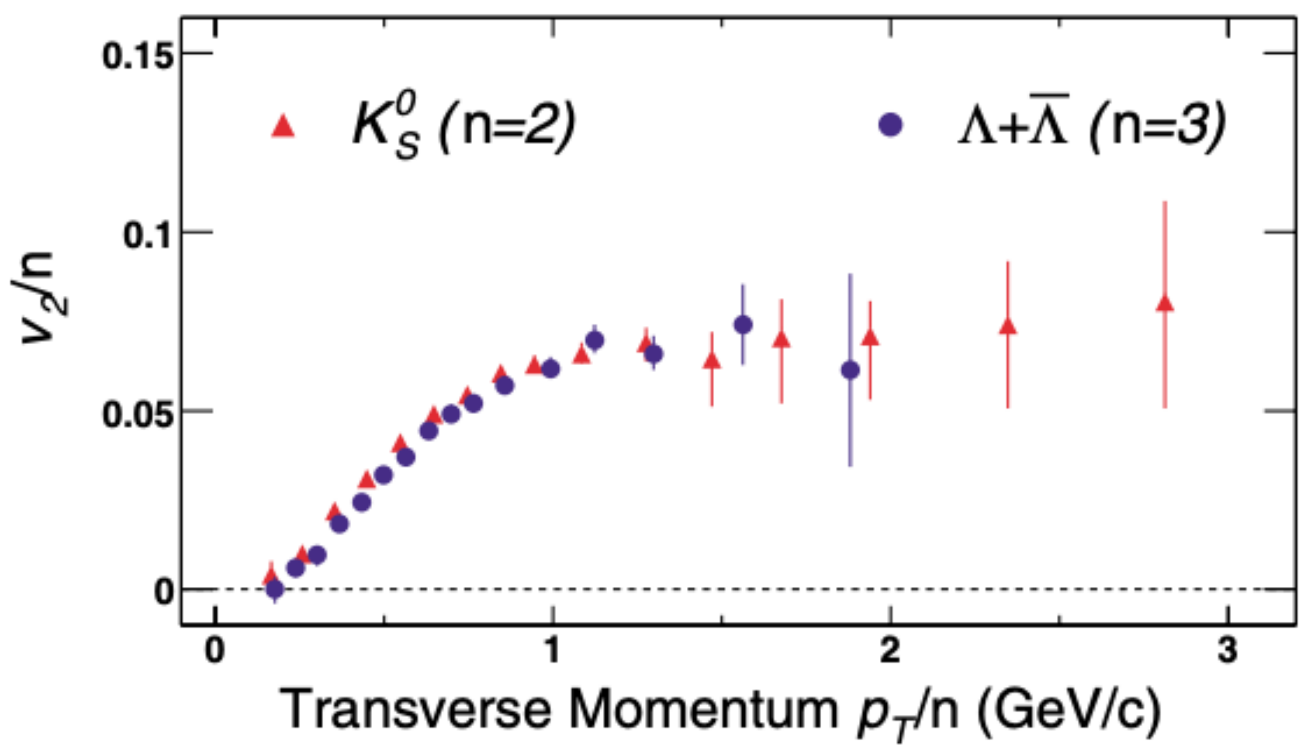
E895, Phys. Rev. Lett. 85, 940 (2000)



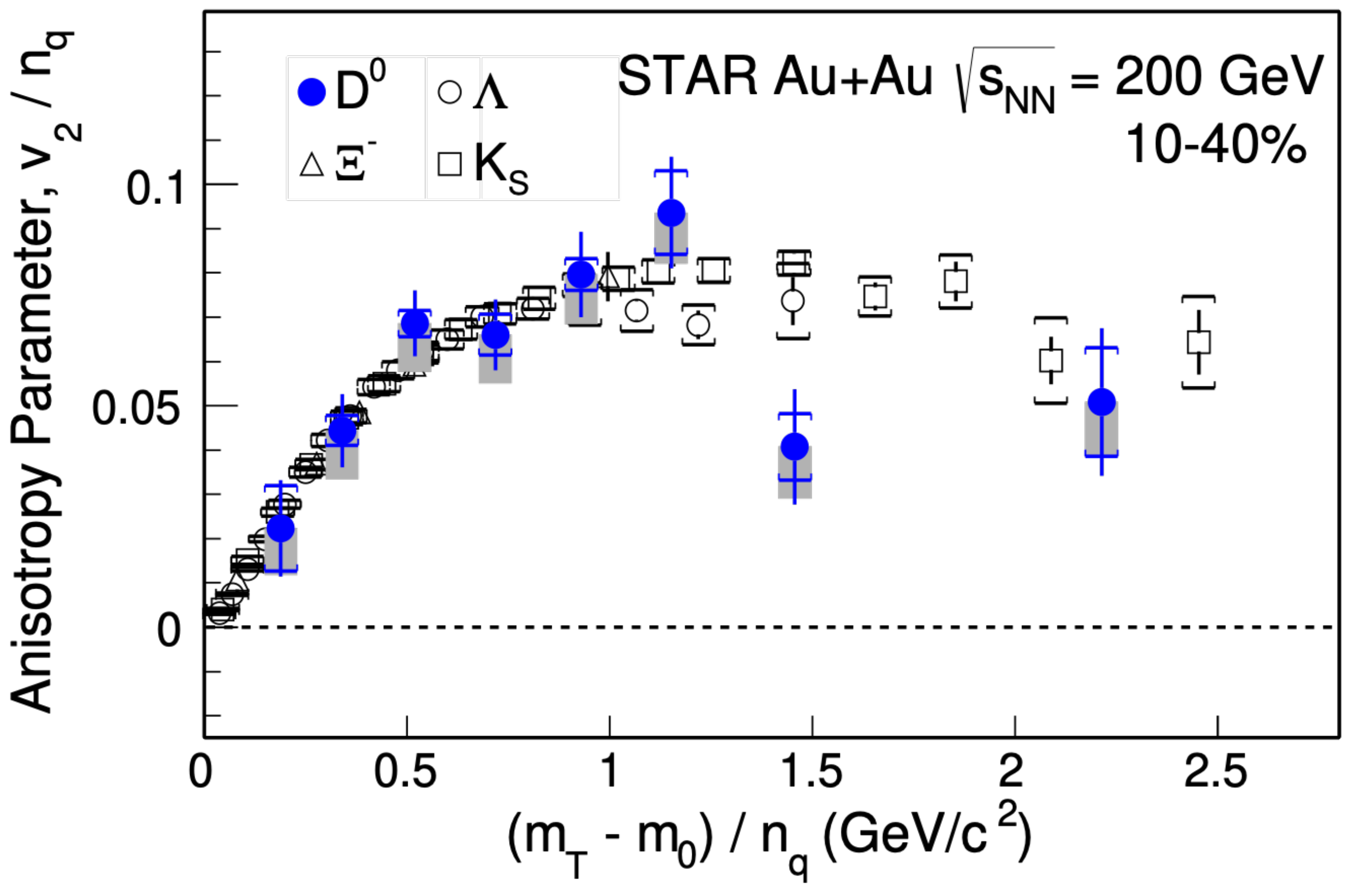
- Bounce-off: Positive flow in positive rapidity
- Au+Au 3.83 GeV: Anti-flow of kaon at low p_T (< 0.7 GeV/c) → Kaon potential?

Motivation: Elliptic flow

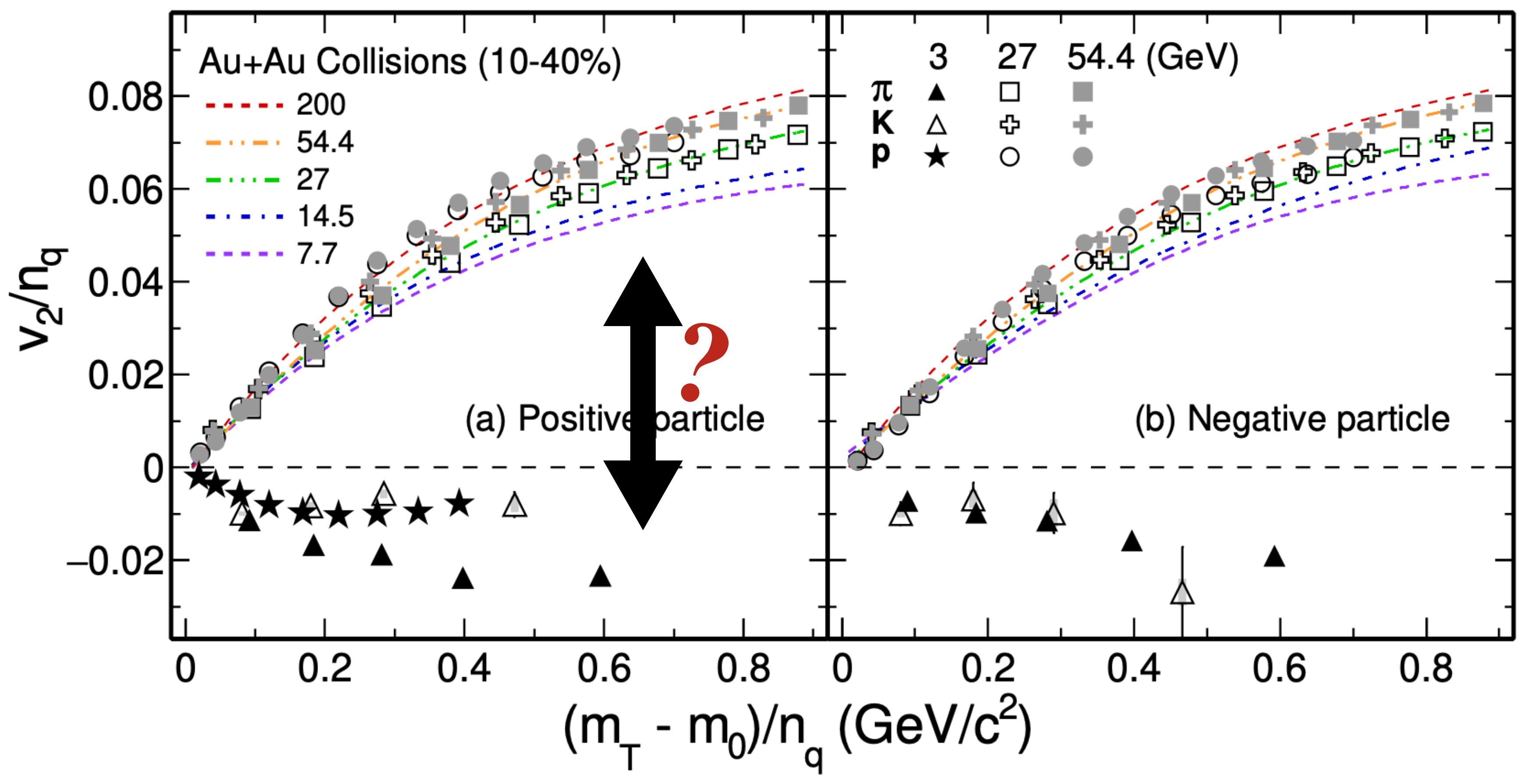
STAR, Phys. Rev. Lett. 92, 052302 (2004)



STAR, Phys. Rev. Lett. 118, 212301 (2017)

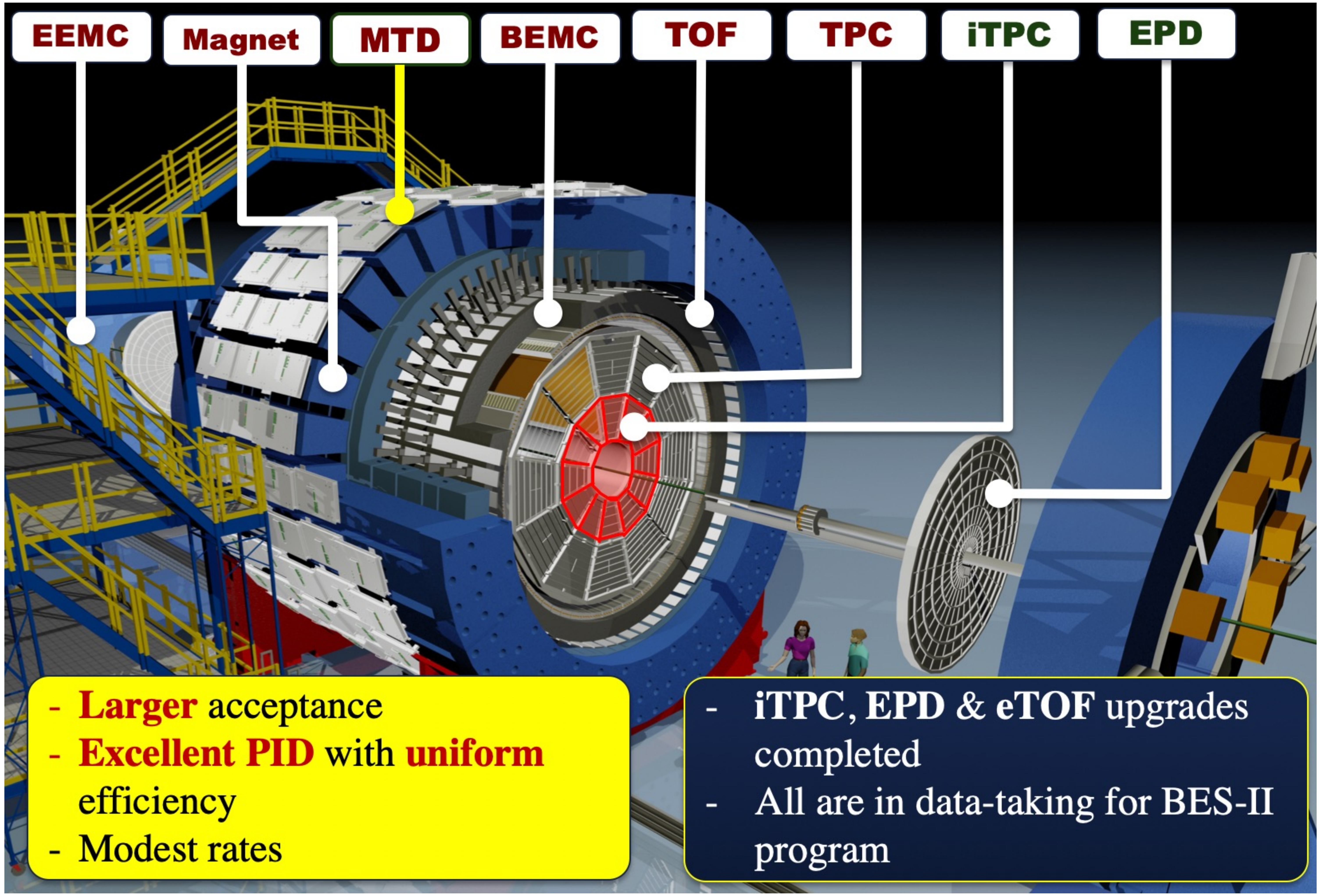


STAR, Phys. Rev. Lett. 110, 142301 (2013)
Phys. Rev. C 93, 14907 (2016), Phys. Lett. B 827, 137003 (2022)



- ➢200 GeV: Partonic collectivity
- ➢3.0 GeV: Hadronic interaction dominates
- ➢Transition in degree of freedom: 3.0 → 7.7 GeV?

Experimental Setup

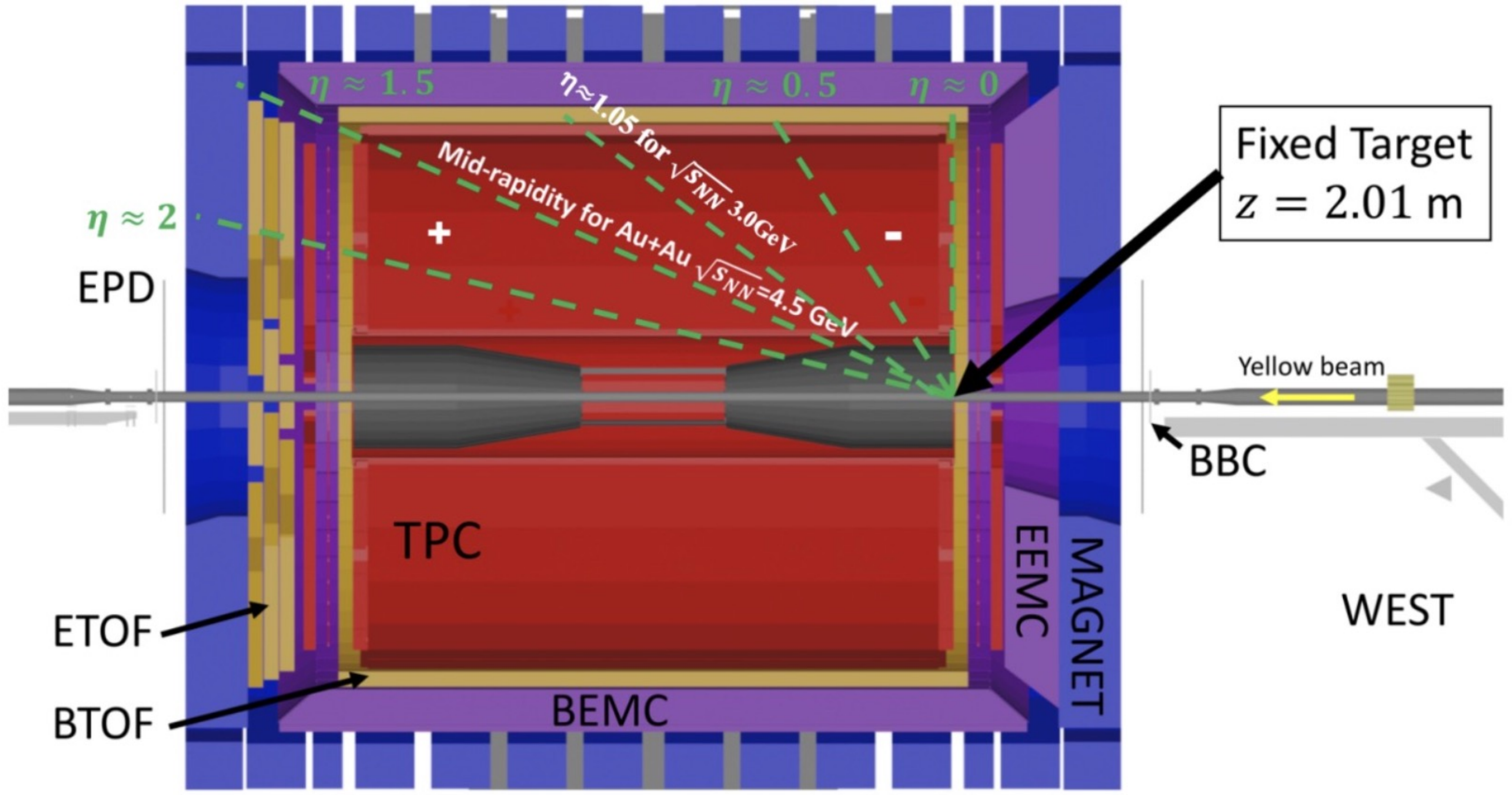


- **Larger** acceptance
- **Excellent PID** with **uniform** efficiency
- Modest rates

- **iTPC, EPD & eTOF** upgrades completed
- All are in data-taking for BES-II program

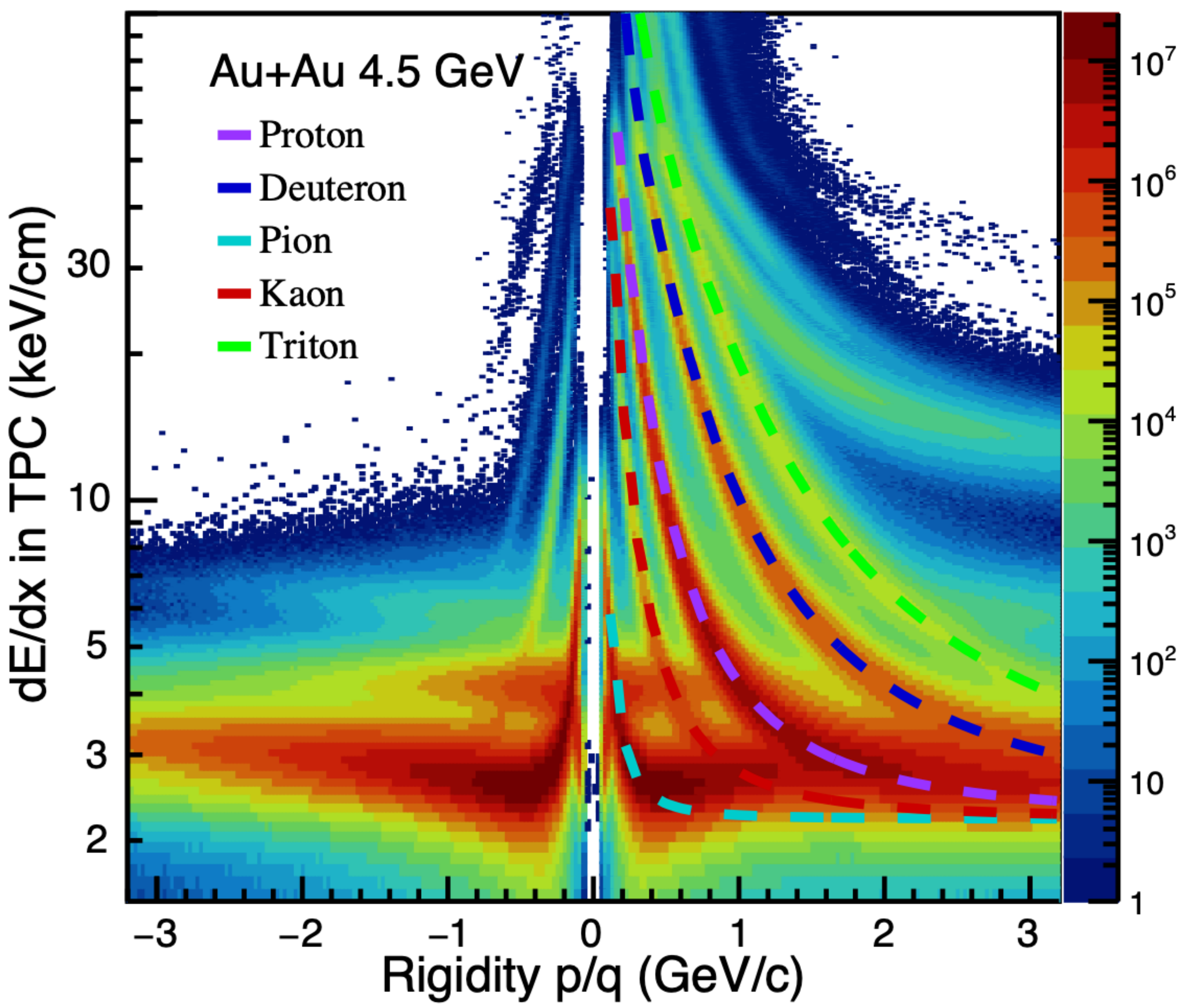
STAR Detector Upgrade:

1) **I**nner-**T**ime **P**rojection **C**hamber
   - Better track quality, Larger acceptance
2) **E**ndcap **T**ime **O**f **F**light
   - Particle identification
3) **E**vent **P**lane **D**etector
   - Event plane determination ($2.1 < |\eta| < 5.1$)

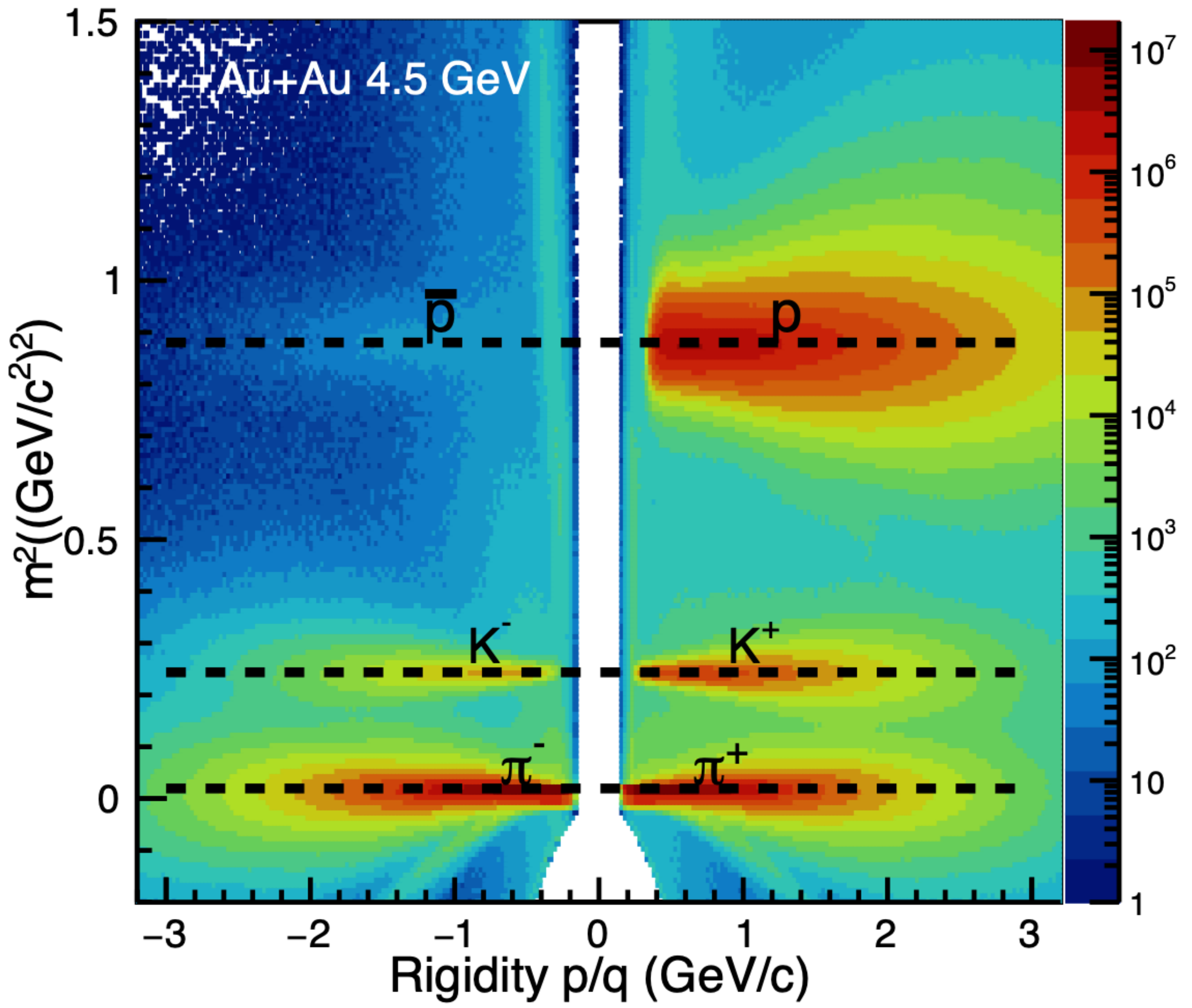


Particle Identification

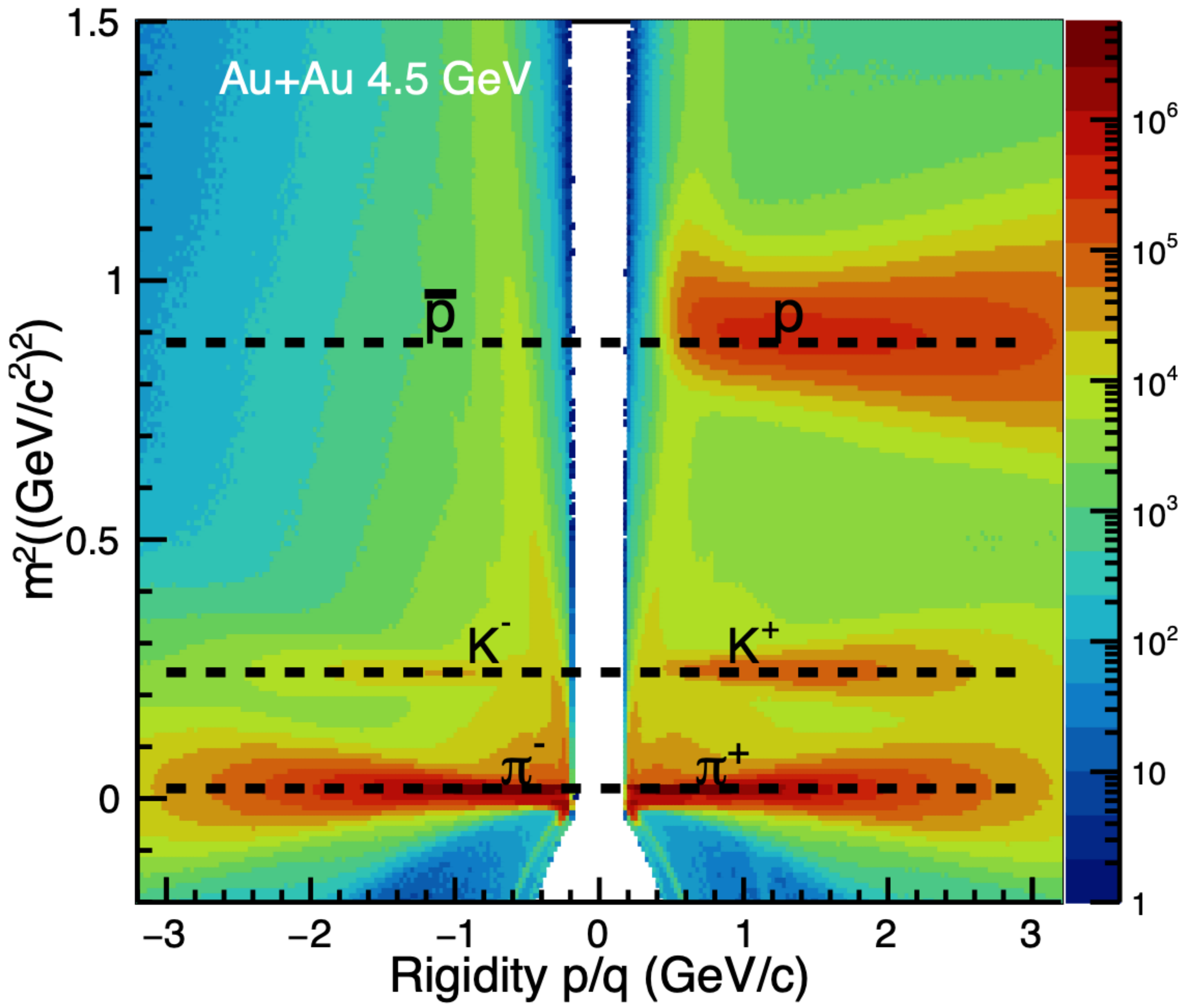
TPC



bTOF



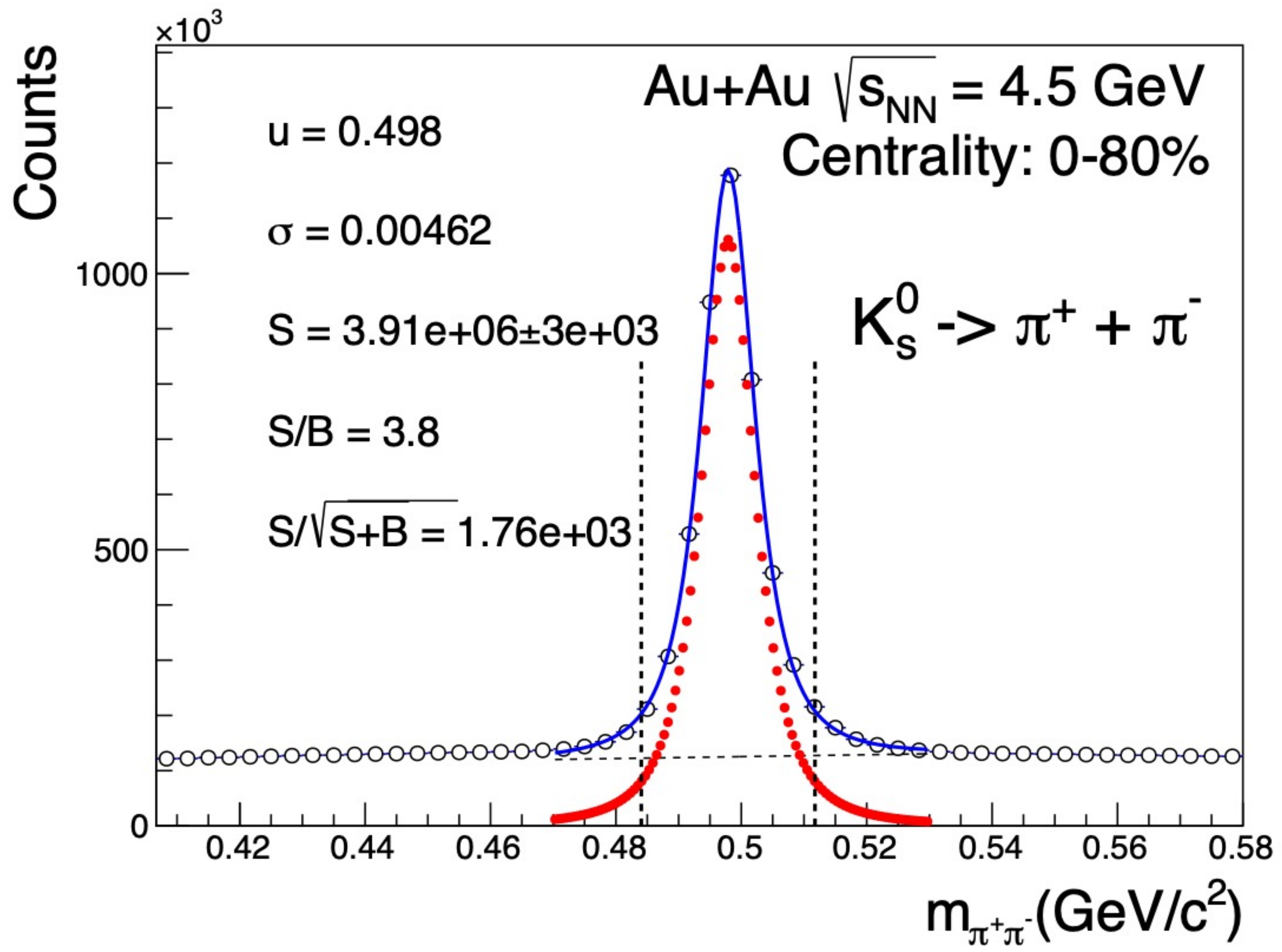
eTOF

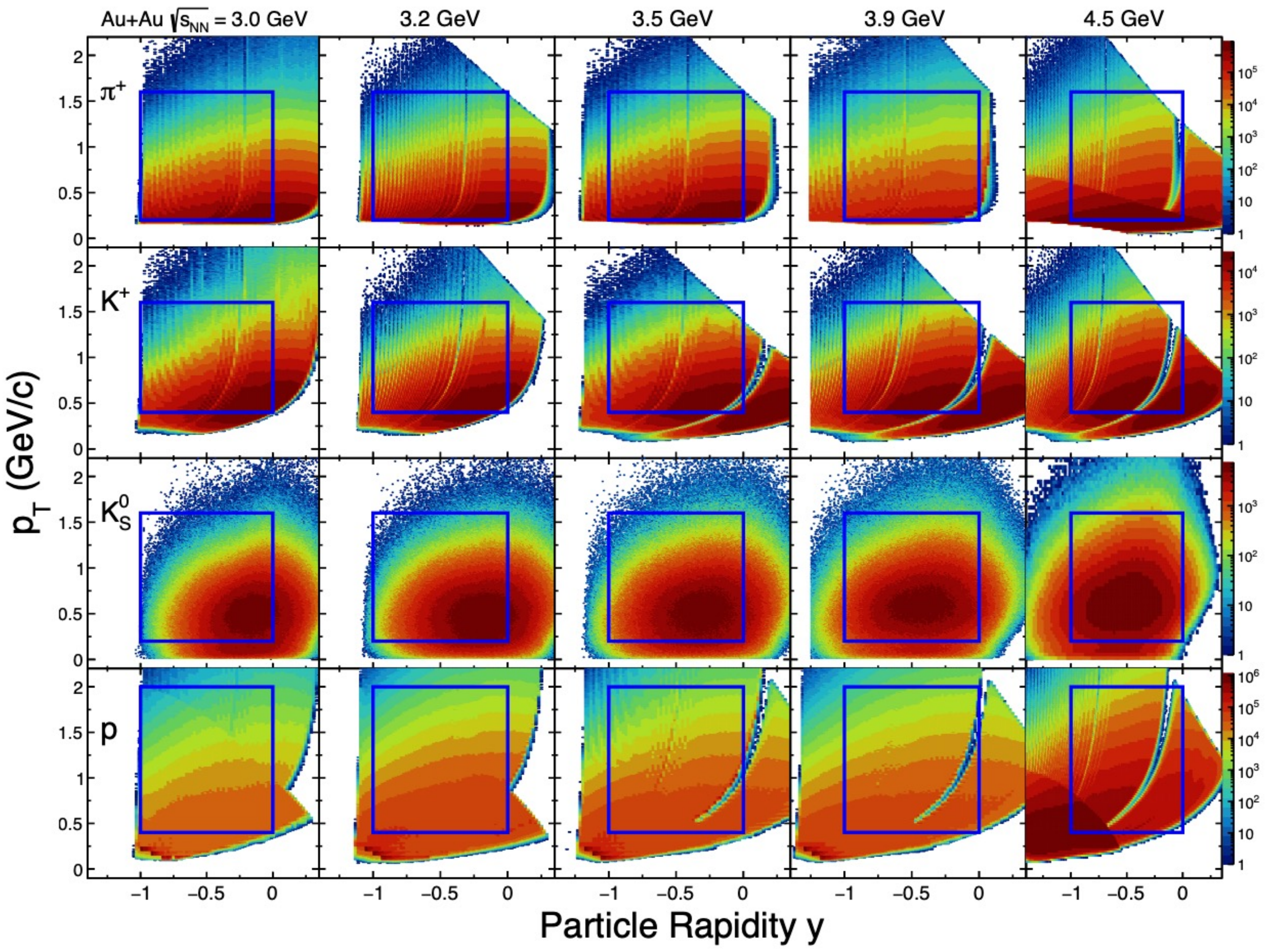


Au+Au (GeV)	**3.0**	**3.2**	**3.5**	**3.9**	**4.5**
Baryon chemical potential (~MeV)	750	700	670	635	590
Events analyzed (M)	260	206	107	94	128

Good particle identification capability based on TPC dE/dx and TOF m^2

Particle Acceptance

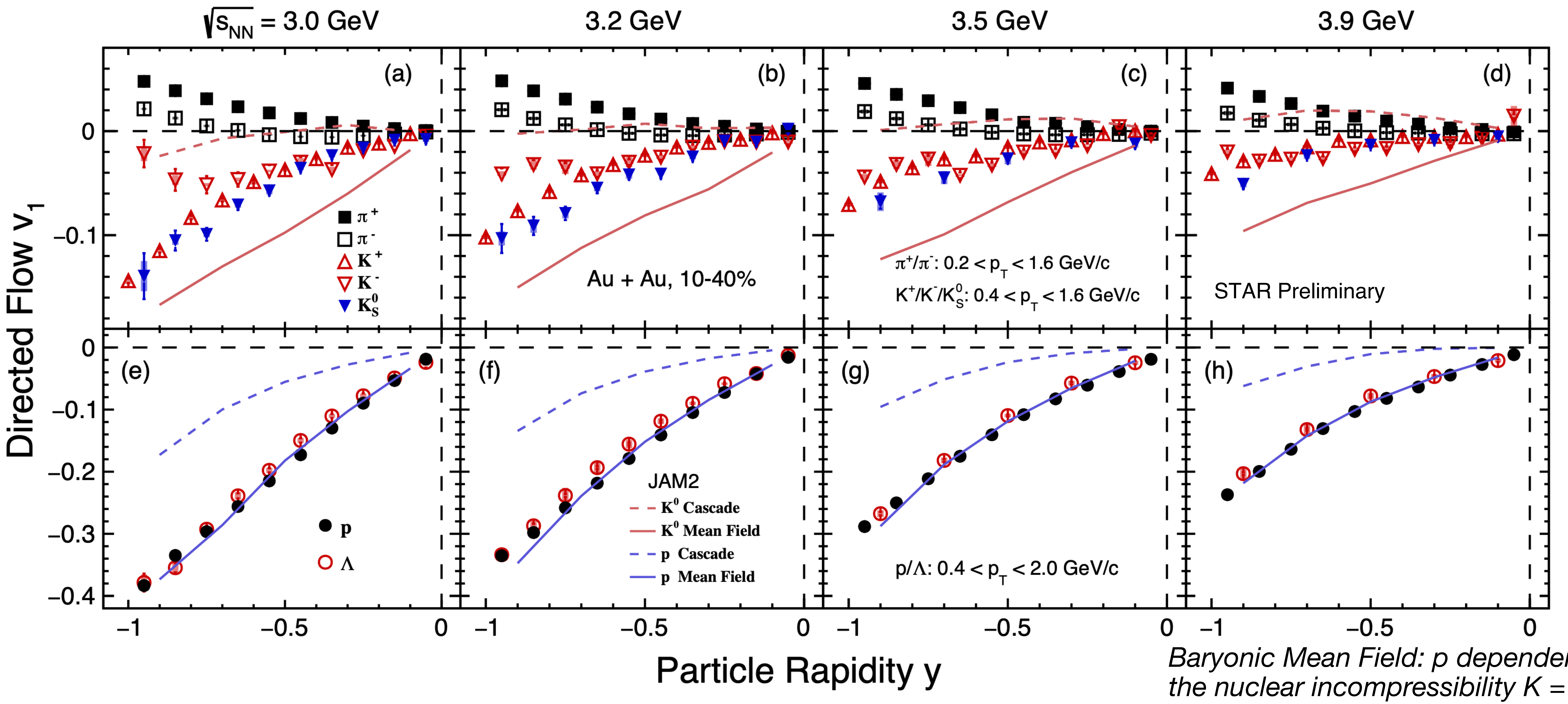




- K_S^0,Λ are reconstructed by invariant mass method (KF particle package)
- Particle rapidity coverage from -1 to 0 (blue boxes)

A. Banerjee, I. Kisel and M. Zyzak, Int. J. Mod. Phys. A 35, 2043003 (2020)

Rapidity dependence of v_1

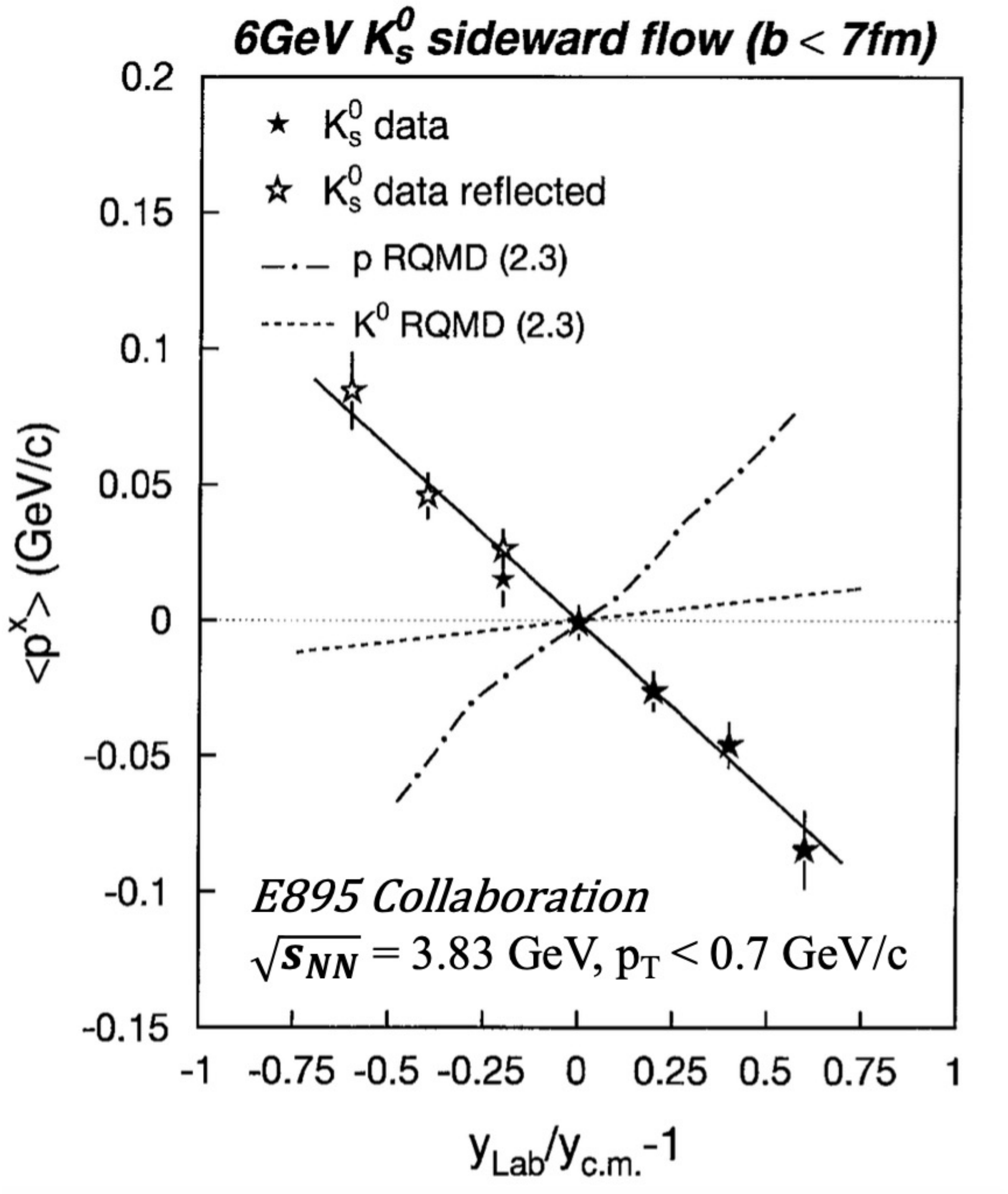


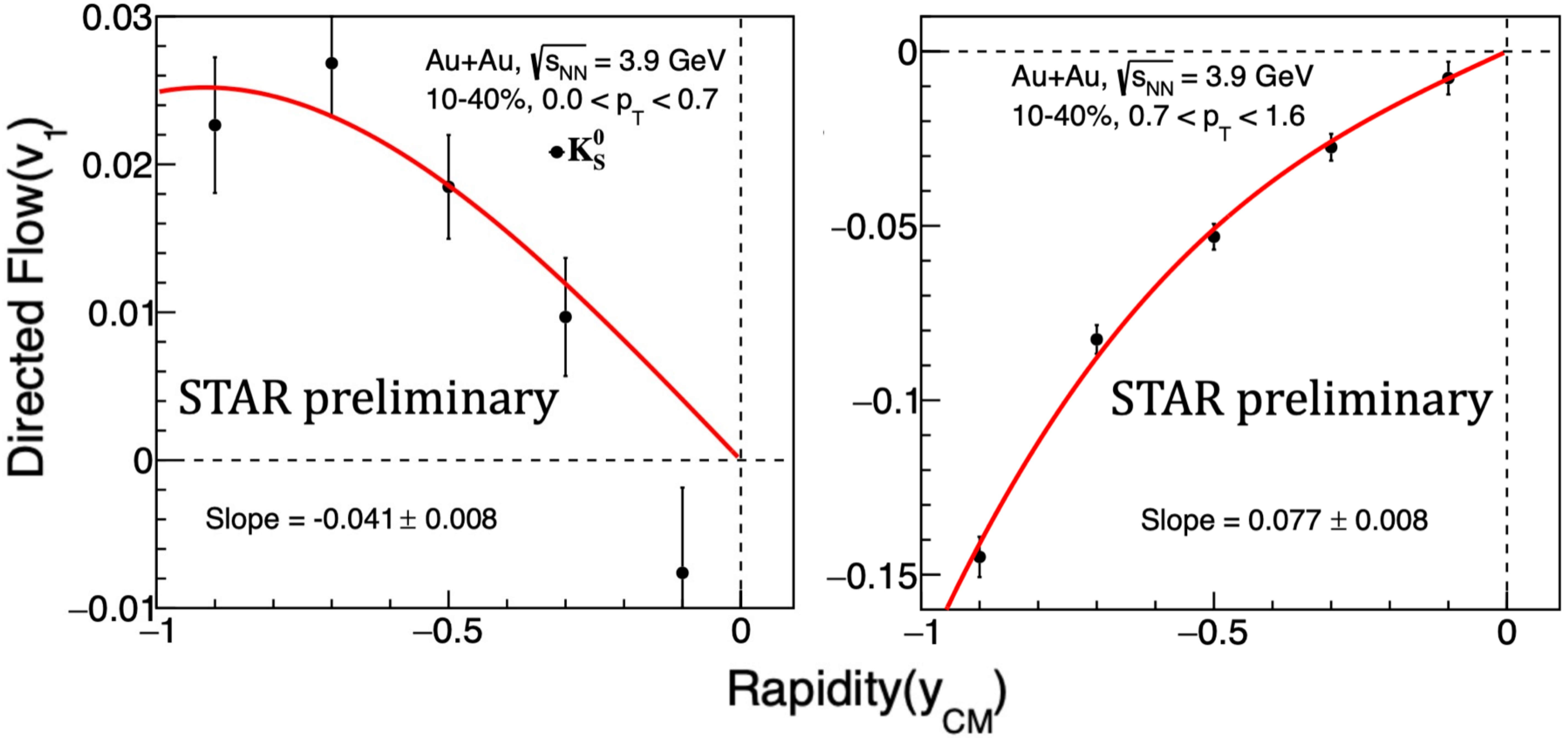
Baryonic Mean Field: p dependent Soft EoS
the nuclear incompressibility K = 210 MeV

Measurements of v_1 vs. rapidity for $\pi^{\pm}, K^{\pm}, K_S^0, p, \Lambda$ at 3.0, 3.2, 3.5, and 3.9 GeV

Anti-flow of Kaon

E895, Phys. Rev. Lett. 85, 940 (2000)

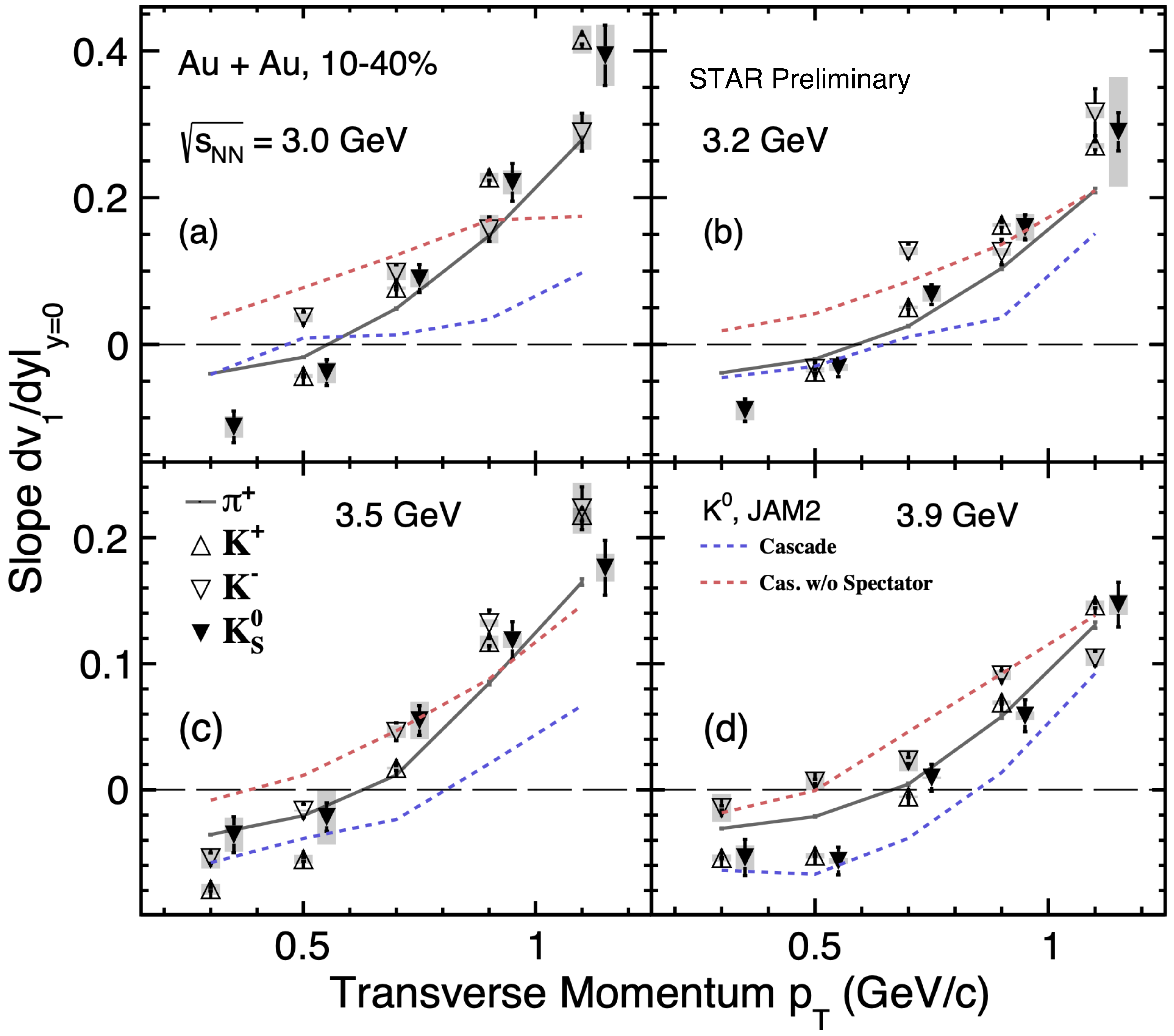




- 3.9 GeV: anti-flow observed for K_S^0 at p_T < 0.7 GeV/c
- Positive directed flow slope of K_S^0 at p_T > 0.7 GeV/c

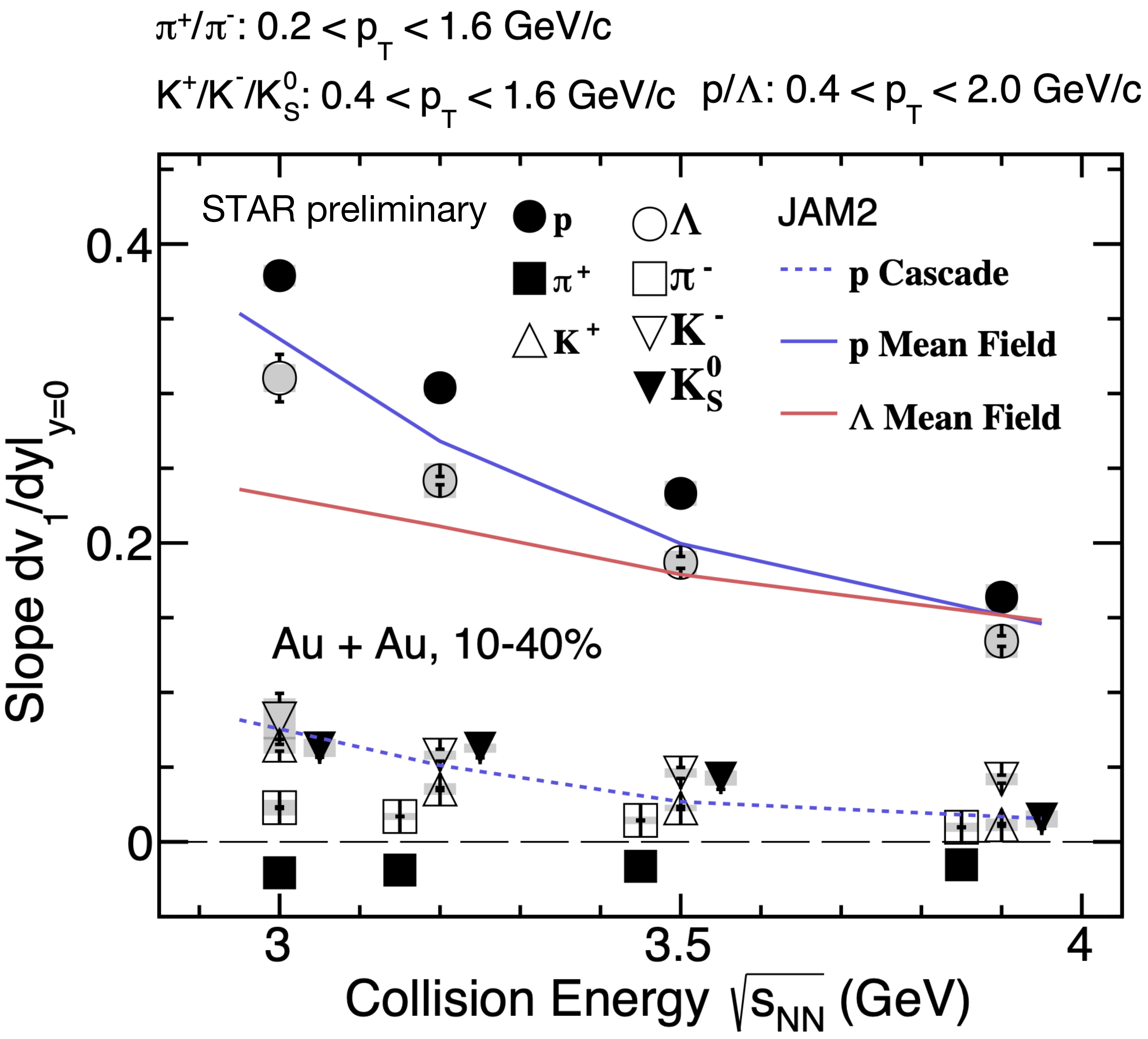
Strong p_T dependence of K_S^0 v_1 slope

p_T dependence of v_1 slope



- Anti-flow of π^+ and $K_S^0, K^\pm$ at low p_T
- Anti-flow could be explained by shadowing effect from spectators

Energy dependence of v_1 slope



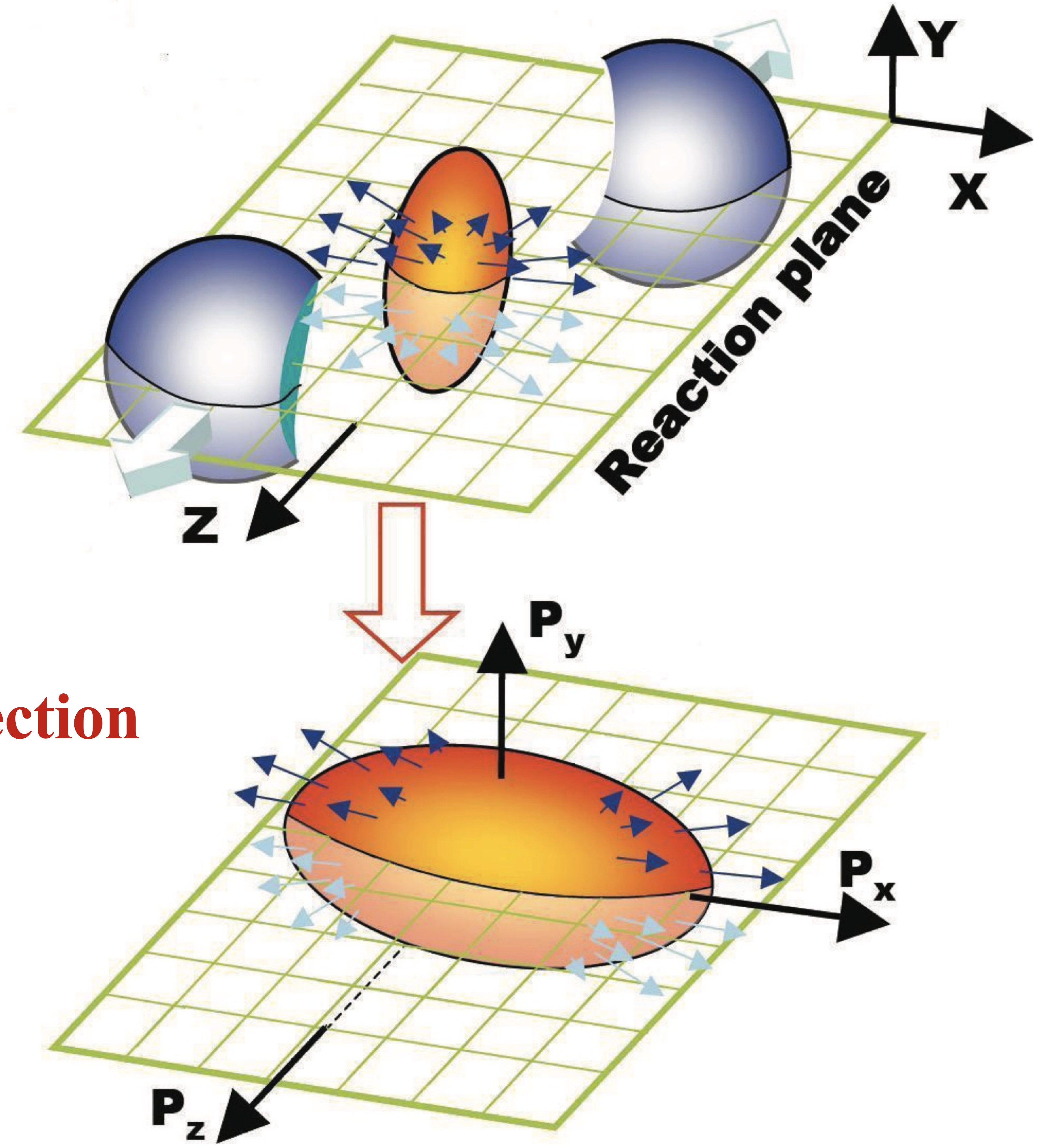
- v_1 slope of baryons drops as collision energy increases
- JAM with baryonic Mean Field better describes data

Mean field potential plays important role

Anisotropic flow

$$v_1 = \cos(\phi - \psi_r) = \langle\frac{p_x}{p_T}\rangle$$

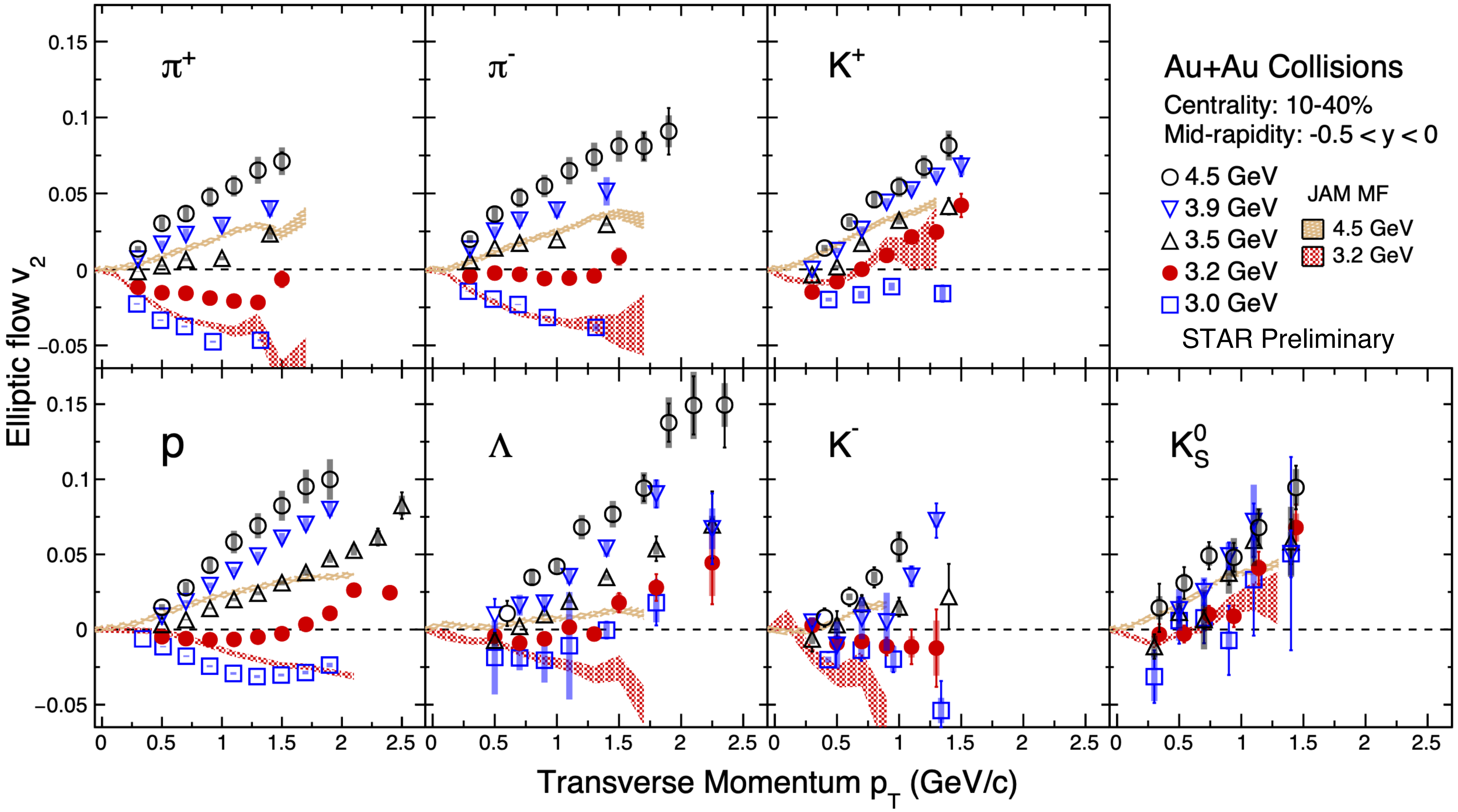
$$v_2 = \cos[2(\phi - \psi_r)] = \langle\frac{p_x^2 - p_y^2}{p_x^2 + p_y^2}\rangle$$



v_1 reflect asymmetry along X direction

v_2 reflect asymmetry on X-Y plane

p_T dependence of v_2 at 3.0 - 4.5 GeV

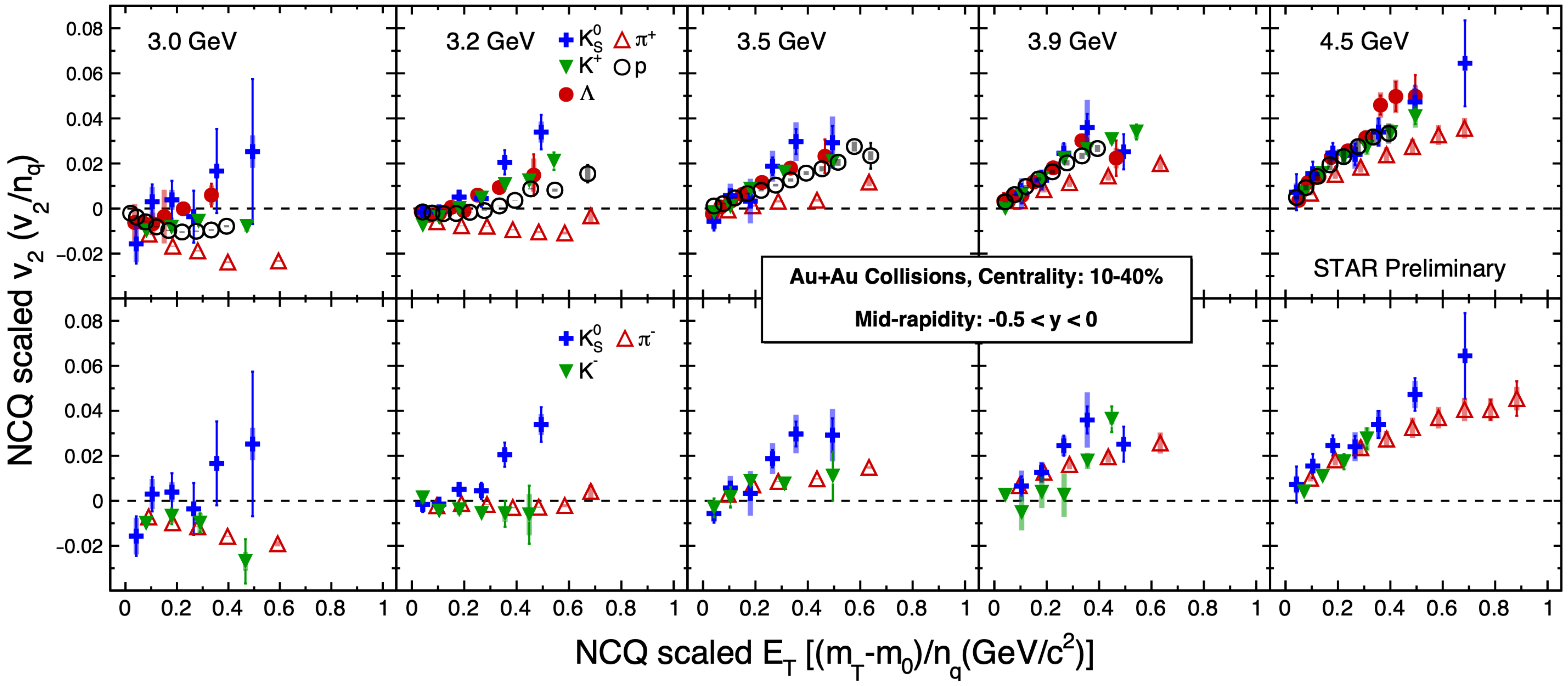


- Clear energy dependence for $v_2(p_T)$ from negative to positive: **Shadowing effect**
- JAM + baryonic Mean Field better describe the 3.2 GeV while underestimate 4.5 GeV data

Baryonic Mean Field: p dependent Soft EoS, the nuclear incompressibility K = 210 MeV

NCQ scaling of v_2 at 3 - 4.5 GeV

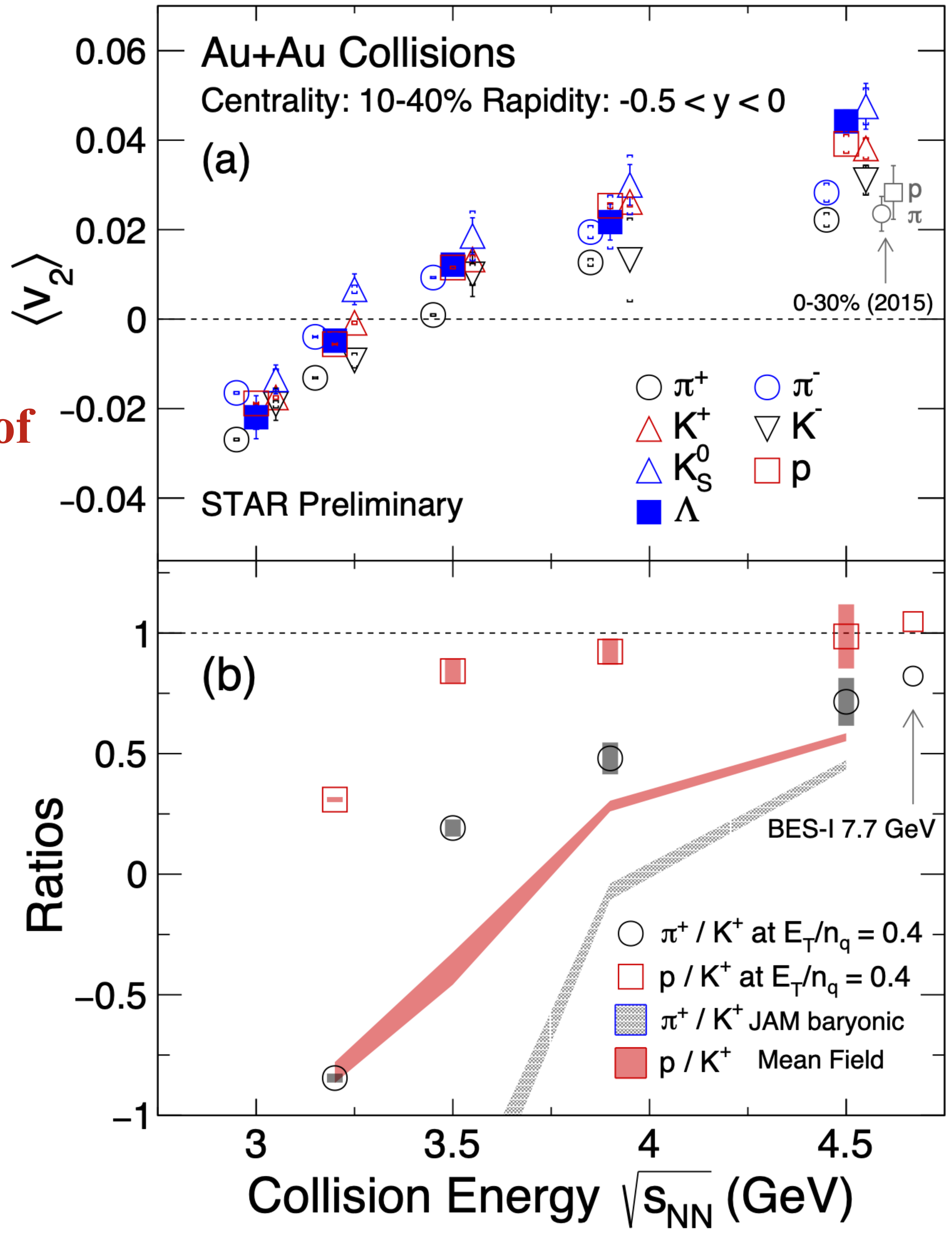
Hadronic interaction



Partonic collectivity

- NCQ scaling completely breaks below 3.2 GeV
- NCQ scaling becomes better gradually from 3.2 to 4.5 GeV

Energy dependence of $\langle v_2 \rangle$



In-plane expansion

Out of plane

- Negative to positive flow: 3 → 4.5 GeV
- The NCQ-scaled v_2 ratio of p/K^+ is close to 1 at 3.9 and 4.5 GeV, while it deviates largely from 1 at 3.2 GeV

STAR, Phys. Rev. C 88, 14902 (2013), Phys. Rev. C 103, 34908 (2021)

Summary

- Anti-flow for $K_S^0, K^{\pm}$ and π^+ observed at low p_T ($\lesssim$ 0.6 GeV/c)
  - **Shadowing effect is important:**

    anti-flow is not unique to the presence of a kaon potential

- NCQ scaling breaks at 3.0 and 3.2 GeV, and gradually restores from 3.0 to 4.5 GeV
  - **Shadowing effect diminishes**
  - **Dominance of partonic interactions at 4.5 GeV**